# APPENDIX B

## SOURCES OF ADDITIONAL TECHNICAL INFORMATION

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**U.S. DOE Sites:**

http://nrel.gov/ Web site for the U.S. Department of Energy's (USDOE) National Renewable Energy Laboratory (NREL), a premier laboratory for renewable energy research & development and a lead lab for energy efficiency research & development.

http://www.nrel.gov/wind/ Web site for the National Wind Technology Center.

http://nrel.gov/energy_resources/ NREL distribution energy web site.

http://www.eren.doe.gov/wind/ Web site for U.S. DOE's Wind Energy Program.

http://www.eren.doe.gov/distributedpower/ and http://www.eren.doe.gov/der/
DOE distributed power homepage.

**Other Sites:**

The following documents and Internet resources provide additional information about wind and solar technology.

http://www.energyinfosource.com Web site for Energy Info Source, Inc., An energy industry publishing company that produces newsletters and reports focusing on current trends in the electric and gas industries. Publications on green power, distributed generation sustainable energy technologies are available at this site.

http://www.windpower This site is home to the Danish Windpower Manfacturers Association and provides " more than 100 animated pages and calculators on wind resources, wind turbine technology, economics, and environmental aspects of wind energy. Also available are links to related sites, articles, statistics, pictures, a reference manual and answers to Frequently Asked Questions. The Table of Contents for the Reference Manual provided at this site http://www.windpower.org/stat/units.htm is as follows:

1. Wind Energy Concepts
2. Energy and Power Definitions
3. Proof of Betz' Law
4. Wind Energy Acoustics
5. Wind Energy and Electricity

    1.Three Phase Alternating Current
    2.Connecting to Three Phase Alternating Current
    3.Electromagnetism Part 1
    4.Electromagnetism Part 2
    5.Induction Part 1
    6.Induction Part 2

6.Wind Energy, Environment, and Fuels
7.Bibliography
8.Wind Energy Glossary

Answers to the following Frequently Asked Questions (FAQs) about Wind Energy are provided at the following site http://www.windpower.dk/faqs.htm

1. Are wind turbines noisy?
2. Do wind turbines really save energy?
3. Are there enough wind resources around?
4. Can wind contribute significantly to electricity production?
5. Is there any progress in wind turbine technology?
6. Is wind energy expensive?
7. Is wind energy safe?
8. Are wind turbines reliable?
9. How much land is required to site wind Turbines?
10. Can wind turbines blend into the landscape?
11. How is the landscape affected after a wind turbine has been dismantled?
12. Do wind turbines bother wildlife?
13. Can wind turbines be placed anywhere?
14. Can wind turbines be used economically in inland areas?
15. How can the varying output from wind turbines be used in the electrical grid?
16. Will wind energy work on a small scale?
17. Can wind energy be used in developing countries?
18. Does wind energy create jobs?
19. Is wind energy popular in countries, which already have many wind turbines?
20. What is the wind energy market like?
21. Why are Danish wind turbines well known around the world?

http://www.awea.org/ American Wind Energy Association web site. Examples of key private sector companies are as follows. Web sites for these companies provide extensive details about turbine options.

AEROMAX Corporation
Atlantic Orient Corporation
Bergey Windpower Company, Inc.
Dutch Pacific L.L.C.
Enron Wind Corporation
Mitsubishi Heavy Industries America
NEG Micon USA, Inc.
Nordex
Northern Power Systems
Southwest Windpower
Synergy Power Corporation
Vestas-American Wind Technology, Inc.
WindTech International, L.L.C.
The Wind Turbine Company
Wind Turbine Industries Corporation

www.solstice.crest.org Solstice, Information service of the Center for Renewable Energy and Sustainable Technology - provides comprehensive index to alternative energy resources.

http://pollution.about.com/cs/photovoltaics/ and http://pollution.about.com/cs/solarenergy/ Research information on photovoltaics and the latest technology in solar energy.

# Design Tools

As wind turbine designs become more complex, computer codes are an increasingly important tool for the wind turbine designer. The National Renewable Energy Laboratory's (NREL's) National Wind Technology Center (NWTC) and its subcontractors have developed a variety of sophisticated computer codes that model wind characteristics, the interactions of the wind with turbine blades, turbine structures, power output, and total wind system operation. These codes help wind turbine designers create new designs or investigate design problems that show up during testing.

This fact sheet briefly highlights design codes and provides directions for obtaining the codes. Selected codes are also available via file transfer protocol from the NWTC home page at http://nwtc.nrel.gov

The Center welcomes industry participation in developing and testing new design tools. Please check the insert entitled *User Facility Agreements* to see how your firm can work with engineers at the Center.

## Turbine Structures

The YAWDYN code models simple blade motion and yaw in two- and three-bladed rotors. This easy-to-learn code is well suited for preliminary design studies. It provides quick estimates of important loads and machine responses to incoming winds. It also performs simple studies of blade pitch or aileron controls.

The FAST code is an intermediate-level structural design code that permits more detailed modeling of the entire turbine, including the effects of yaw motion, two- and three-bladed rotors, and two-bladed, teetering hubs. Its blade-modeling capabilities include elastic flap and edgewise motions. It can model tower motions in two directions, parallel and perpendicular to the wind. It can also model drivetrain torsional flexibility. With the FAST code, designers can model machine start-up, shutdown, variable-speed operation, and constant-rotor-speed operation. Developed at Oregon State University, the code is currently being validated at NREL, where researchers are adding a control simulation for modeling blade pitch and aileron controls.

The ADAMS-WT preprocessor and the ADAMS software constitute the most comprehensive computer model of a wind turbine system available. ADAMS produces a very complex turbine model, including detailed operational modes, loads, and turbine responses to steady winds and turbulence. Because of its complexity, it is best suited for the analysis of complex problems observed during prototype testing and final design of a new wind turbine when designers have detailed turbine input data.

Warren Gretz, NREL PIX 00359

*NREL researchers use the ADAMS-WT code to build a wind turbine on the computer screen. Once the turbine is built, ADAMS software performs a detailed analysis of its structure and operation.*

The ADAMS-WT preprocessor uses a graphical interface to assist the user in setting up an ADAMS model. To set up the model, the user must input detailed design data on the characteristics of blades and other components. Without the preprocessor, developing a model that runs correctly can take months; with the preprocessor, developing a model takes a few days.

NREL has prepared user manuals for ADAMS-WT and ADAMS. The manuals include examples of turbine configurations such as a simple two-bladed, teetering-hub machine with blade flap and machine yaw. To help the user better understand the model-building process, examples of elastic blades and detailed tower and drivetrain models are also included.

Even with ADAMS-WT, the ADAMS software can take months to learn. Subcontractors can come to the Center for help using ADAMS. NREL recommends that turbine designers consider a week-long course offered by Mechanical Dynamics, Incorporated, the software developer.

## Inflow

SNLWIND-3D, a variant of a code developed by Sandia National Laboratories, simulates wind flowing into a turbine rotor. The code was designed for use with other design codes, including YAWDYN, FAST, and ADAMS. SNLWIND-3D creates different types of turbulent winds for the turbine under study. It simulates turbulent inflow to a single turbine or a multi-row wind power plant. The code also simulates turbulence according to specifications from the International Electrotechnical Commission.

## Aerodynamics

Used for both design and analysis, the PROPPC code predicts the power output of turbine rotor designs. When the user specifies blade geometry, shape, and airfoil performance characteristics, PROPPC will calculate the rotor's power curve.

The WT-PREP code prepares an input data set of airfoil characteristics, such as the coefficients of lift and drag, for the PROPPC code. WT-PREP interpolates performance characteristics between Reynolds numbers and between different airfoils, saving the user significant amounts of time in using PROPPC.

An electronic data table for NREL-designed airfoils developed since the mid-1980s is also available for use with PROPPC. The data table contains the coefficients of lift, drag, and moment for more than 30 different airfoils. The data table, the PROPPC code, and the WT-PREP code are available from NREL.

PROP93 is a graphics-based version of PROPPC, developed and sold by the Alternative Energy Institute.

The PROPID code works the opposite of the PROPPC code. If a designer specifies the performance characteristics of a rotor, the code calculates the blade shape that will produce the desired performance. For example, given a range of five blade lengths and a range of five peak power ratings, PROPID can produce 25 candidate blade geometries within minutes.

## Where To Obtain Turbine Design Codes

YAWDYN, blade motion, yaw
Dr. A.C. Hansen
Department of Mechanical Engineering
University of Utah
Salt Lake City, Utah 84112
(801) 581-4145 fax: (801) 581-8692
e-mail: hansen@me.mech.utah.edu

FAST, turbine structures
Dr. Robert E. Wilson
Department of Mechanical Engineering
Oregon State University
Corvallis, Oregon 97331-6001
(541) 737-2218 fax: (541) 737-2600
wilsonr@ccmail.orst.edu

ADAMS, complete wind turbine system
Dr. Andrew S. Elliott
Mechanical Dynamics, Incorporated
6530 East Virginia Street
Mesa, Arizona 85215
(602) 985-1557 fax: (602) 985-1559
e-mail: aelli@adams.com

SNLWIND-3D, wind inflow
Neil Kelley
National Renewable Energy Laboratory
National Wind Technology Center
1617 Cole Boulevard
Golden, Colorado 80401
(303) 384-6923 fax: (303) 384-6901
e-mail: neil_kelley@nrel.gov

PROPPC and WT-PREP, power performance
NWTC Library
National Renewable Energy Laboratory
National Wind Technology Center
1617 Cole Boulevard
Golden, Colorado 80401
(303) 384-6963 fax: (303) 384-6999
e-mail: jennifer_doran@nrel.gov

PROP93, power performance
Dr. Vaughn Nelson or Ken Starcher
Alternative Energy Institute
West Texas A&M University
Box 248
Canyon, Texas 79016
(806) 656-2298 fax: (806) 656-2733
e-mail: aei@wtamu.edu

PROPID, blade shape
Dr. Michael S. Selig
Dept. of Aeronautical and Astronautical Engineering
University of Illinois at Urbana-Champaign
306 Talbot Laboratory
104 South Wright Street
Urbana, Illinois 61801-2935
(217) 244-5757 fax: (217) 244-0720
e-mail: m-selig@uiuc.edu
http://uxh.cso.uiuc.edu/~selig/


NREL

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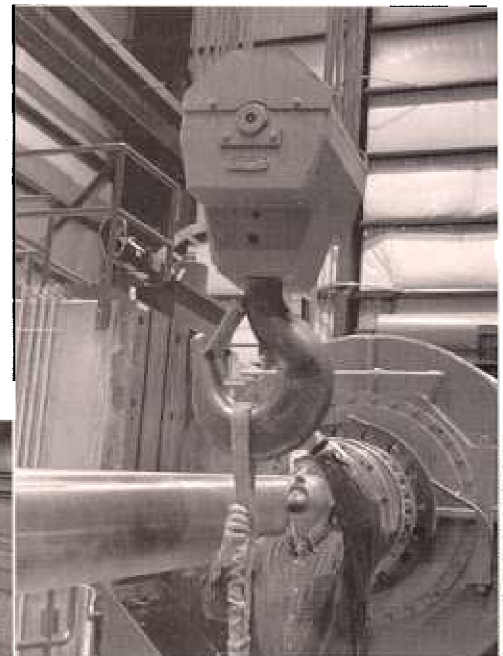
# DYNAMOMETER TEST BED

The National Renewable Energy Laboratory's (NREL's) Dynamometer Test Bed is one of a kind. It offers wind industry engineers a unique opportunity to conduct lifetime endurance tests on a wide range of wind turbine drivetrains and gearboxes at various speeds, using low or high torque. Located in a 7500-ft$^2$ building at the National Wind Technology Center near Boulder, Colorado, the 2.5-megawatt (MW) Dynamometer Test Bed was developed to help researchers improve the performance and reliability of wind turbines and ultimately reduce the cost of the electricity they generate. By testing full-scale wind turbines, engineers from NREL and industry hope to understand the impact of various wind conditions with the goal of improving hardware designs.

Wind turbine designers are working to increase the field lifetime of wind turbines by decreasing the loads on components or by making the components more resistant to wear. Wear on drivetrains is an important factor in turbine reliability. Drivetrains contain many components that work together as a system. Each of these components is the subject of design and manufacturing improvements that can be tested on the dynamometer.



Warren Gretz, NREL/PIX08570

*A 50-ton electric bridge crane operates 30 feet above the test table to move the large test drivetrains into position.*

Warren Gretz, NREL/PIX08571

*Dynamometer Test Bed offers industry engineers a unique opportunity to conduct lifetime endurance tests.*

A few months of endurance testing on NREL's Dynamometer Test Bed can simulate the equivalent of 30 years of use and a lifetime of braking cycles, thus helping engineers to determine which components are susceptible to wear. These endurance tests require several months of continuous unattended operation. The test bed's sophisticated Supervisory Control and Data Acquisition (SCADA) System monitors the critical test parameters and can shut down the test if abnormal conditions are detected.

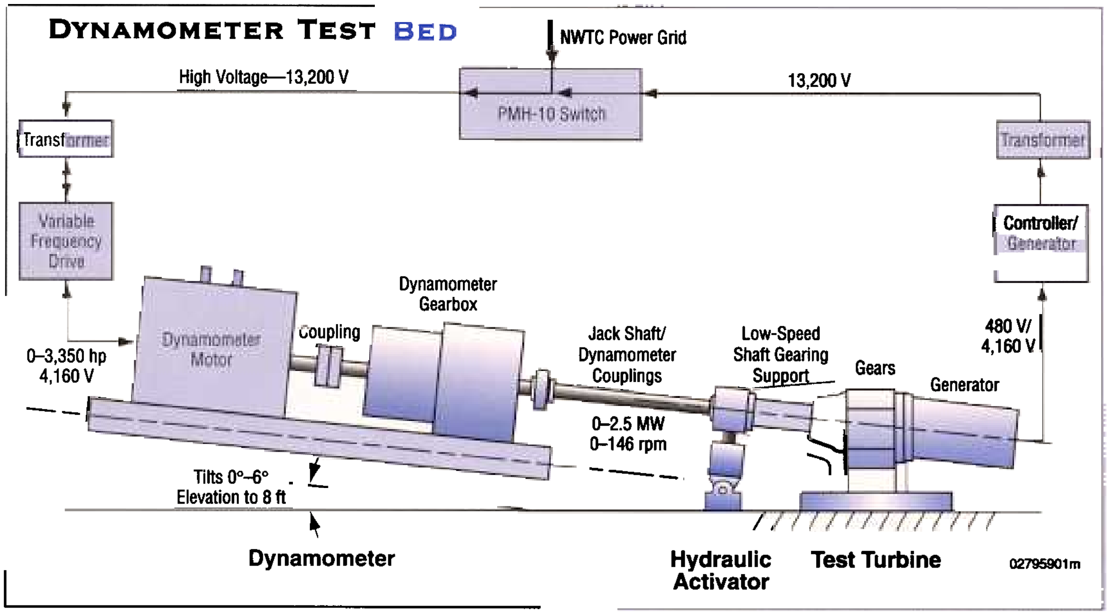
In addition to testing turbines from industrial partners, the new test bed will be used to test prototype turbines from the DOE Turbine Development Program. These tests will confirm the benefits of new approaches and identify problems for redesign well before machines are deployed for field testing.

NREL's Dynamometer Test Bed includes a powerful 3,350-horsepower (hp) electric motor coupled to a 2.5-MW, three-stage epicyclic gearbox that can produce variable speeds from 0 to 146 revolutions per minute (rpm) and run at torque levels up to 9.6 million inch-pounds to simulate the effects of various wind conditions. Its flexible design allows it to couple with the shaft position of any wind turbine system from 100 kilowatts (kW) to

2 MW in size. A 50-ton electric bridge crane operates 30 feet (9.1 meters) above the test table to move the large test drivetrains into position.

In addition to gearboxes and brakes, the dynamometer can test all the other components of the drivetrain—the control system, the generator, the fault logic controls, and more. Tests can also be conducted in conjunction with hydraulic pressure or electric cranes to apply transverse or ancillary loading to a rotating shaft or coupling.

## Dynamometer Test Bed




## Types of Testing

Gearbox/drivetrain endurance testing—Endurance testing demonstrates the fatigue life of a particular gearbox. Testing conditions require high steady-state power levels that vary from 1.3 to 1.8 times the rated capacity of the test article and the test must run for several months of continuous unattended operation. Endurance testing may also require the application of significant transient load cycles that are part of a long-term operating spectrum. Transverse shaft loads may also be applied using hydraulic actuators.

Turbulent wind simulation testing—This type of testing demonstrates the proper operation of the wind turbine's control system under design turbulent conditions. Random wind turbulence is translated into shaft torque by a computer algorithm using inputs from the turbine's own controller. Severe stochastic torque conditions are simulated demanding that the turbine system perform at its limits.

Transient load testing—Transient load testing applies extreme transient torsional loading to the drivetrain or drivetrain components by applying the system's own brake or starting system. System inertia is matched by using the regenerative power system of the electric variable-speed drive. Transverse loads may be applied to driveshafts, bearing housings, or yaw systems to re-create extreme wind load design cases.

Direct-drive (low-speed) generator testing—This type of test uses a direct connection between one of the output driveshafts and the generator. The dynamometer test bay has a pit built into the floor to accommodate generator designs that may have an oversized radial dimension. In these instances, part of the generator may be dropped in the pit below the surface of the test bay floor to facilitate proper alignment of the shafts.

High-speed generator testing—A high-speed generator test is conducted by directly coupling the test article to the north-pointing shaft end of the drive motor. Tests of this kind may be run continuously and unattended.

more information please contact: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In a remote Alaskan village, wind turbines and back up diesel generators provide electricity for lighting, heating, and hot water on a short winter day. This is one of many hybrid power systems researchers can simulate at the National Renewable Energy Laboratory's (NREL's) Hybrid Power Test Bed at the National Wind Technology Center (NWTC).

Hybrid power systems combine multiple power sources such as wind turbines, photovoltaic (PV) arrays, diesel generators, and battery storage systems. They typically are used in remote areas, away from major electric grids.

The Hybrid Power Test Bed is designed to assist the U.S. wind industry in developing and testing hybrid power generation systems. Using simulated village loads, researchers can evaluate the interaction of these power sources under realistic conditions at the test bed. Design engineers are able to work through actual problems the system might encounter in the field.

The test bed allows engineers to evaluate system performance, cost-effectiveness, and reliability using real or simulated solar and wind energy resources. Simulated energy resources allow designers to repeat experiments as they improve system designs. This feature is important for developing new components, advanced hybrid systems, and dispatch and control systems.

U.S. wind companies can use the Hybrid Power Test Bed to train customers from other countries. By providing technical assistance to potential users, the Center encourages the growth of international markets for the U.S. wind industry.

# Hybrid Power Test Bed

## Test Bed Capabilities

Warren Gretz, NREL PIX 02142

*The Atlantic Orient Corporation AOC 15/50 wind turbine, shown here, operates in combination with a diesel generator, rotary converter, battery storage, and system controller at the National Wind Technology Center. The 50-kW hybrid power system was developed by New World Power Technology Company.*

Engineers can evaluate the moment-by-moment dynamics of hybrid power system operation, gather data on long-term performance, or demonstrate innovative design concepts with the Hybrid Power Test Bed. High-speed data acquisition equipment monitors power quality, harmonic distortion, and electrical transients. A village load simulator—a load bank with resistive and inductive elements—can create power factors down to 0.5, allowing test engineers to evaluate system operation under severe conditions that may be encountered in real power systems. Engineers can also investigate the power system's dynamic response to sudden load changes and to conditions of phase imbalance or loss of phase.

Engineers can evaluate the long-term performance of a hybrid power system, including its energy delivery (in kilowatt-hours) and diesel fuel consumption. They can monitor wind speed, insolation, and the performance of battery energy storage. They can characterize system performance under a range of operating conditions, evaluate alarms, emergency shut-down procedures, and other critical functions.

The research test bed provides a good environment for developing, testing, and evaluating new concepts with less technical and financial risk than proving them in the field at a remote location. New power conversion devices, emerging energy storage technologies, prototype control systems, and innovative system architectures are examples of concepts that could be evaluated using the Hybrid Power Test Bed.

## Test Bed Features

The Hybrid Power Test Bed boasts a number of unique features, including the ability to test up to three hybrid power systems simultaneously, use either real or simulated renewable energy sources, simulate a local electric grid, test with real or simulated village loads, and test wind turbine systems producing direct or alternating current (DC or AC).

A custom-designed switch panel with three AC and three DC buses gives the test bed the flexibility to connect or disconnect various system components to meet the objectives of a specific testing program. The switch panel can connect selected components, with combined capacities of up to 100 kW, onto common power buses. Engineers can rapidly change testing configurations by opening and closing a few switches.

Simulated renewable energy sources allow engineers to conduct repeatable testing. A large induction generator functions as a 75-kW AC source simulator. The DC source simulator is a solid-state device that provides up to 20 kW of reproducible DC power.

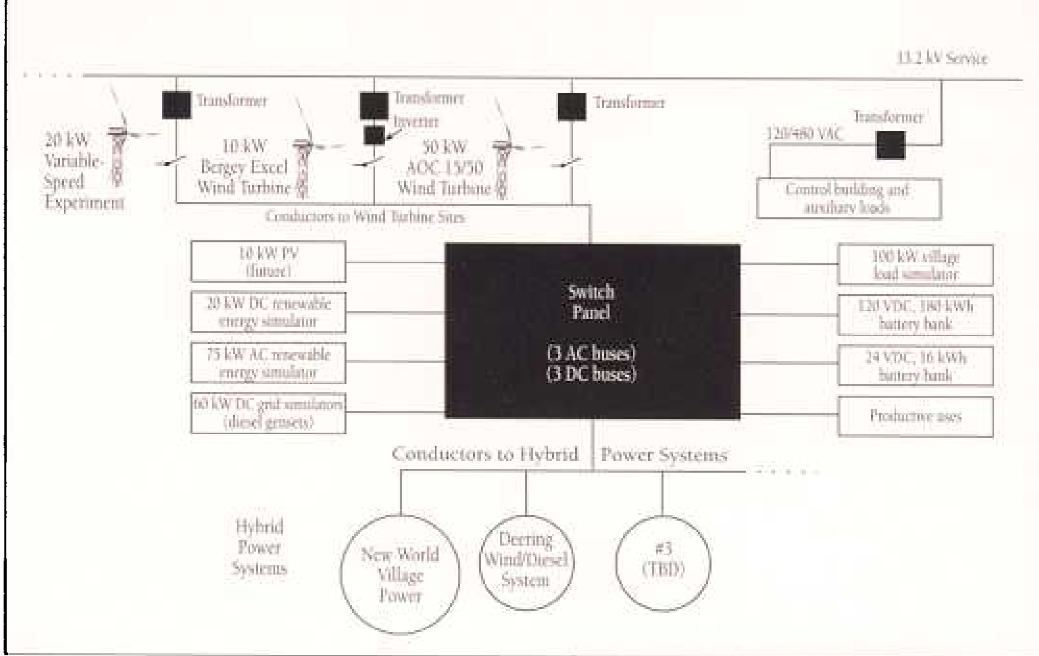
Two 60-kW diesel generator sets are available for use in hybrid systems under test. They may also serve as grid simulators, allowing researchers to test a hybrid power system's ability to synchronize its power output and connect with an existing small grid.

Renewable energy technologies at the facility include three wind turbines, rated from 10 to 50 kW. A PV array between 10 and 20 kW is planned. The Center's good solar and wind resources allow a full range of power system testing under normal operating conditions.

The test bed incorporates a 100-kW village load simulator. The computer-controlled simulator mimics typical electric loads for a small village. The test bed also has the flexibility to incorporate real village loads such as power tools, lighting systems, water pumps, or an icemaker into its tests.

The Hybrid Power Test Bed includes a personal-computer-based control and data acquisition system with a graphical interface.

## Hybrid Power Test Bed




## Hybrid Power Test Bed Equipment

| Component | Rating |
|---|---|
| AOC 15/50 Wind Turbine | 50 kW |
| Bergey Excel Wind Turbine | 10 kW |
| Variable-Speed Wind Turbine | 20 kW |
| PV Array (to be added) | N/A |
| DC Renewable Energy Simulator | 20 kW |
| AC Renewable Energy Simulator | 75 kW |
| Diesel Gen-Set Grid Simulator | 60 kW |
| Two Village Load Simulators | 100 kW |
| DC Battery Banks | 24 and 120 volts |

For more information, please contact

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e-mail: jimg@nrel.gov
http://nwtc.nrel.gov

## Hybrid2 Software

The National Renewable Energy Laboratory and the University of Massachusetts developed Hybrid2, a computer simulation of the long-term performance of hybrid systems. The software models a range of system configurations, including multiple wind turbines, multiple diesel generators, a PV array, battery storage, various power-conversion devices, and different types of loads. It can be used to predict the technical and economic performance of hybrid power system designs. It runs under Windows on a personal computer. Hybrid2 is available, along with an electronic library of input data, from NREL. To request Hybrid2, call (303) 384-7401 or send e-mail to Hybrid2@nrel.gov.

NREL
A national laboratory of the U.S. Department of Energy

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# STRUCTURAL TESTING

At the National Wind Technology Center (NWTC), researchers measure their success by the number of blades they fail. Ultimate static-strength testing, in which blades are tested to failure, is just one type of blade structural evaluation available to the wind industry. NWTC researchers conduct a full range of structural evaluations including ultimate static-strength, fatigue, vibration, and nondestructive tests.

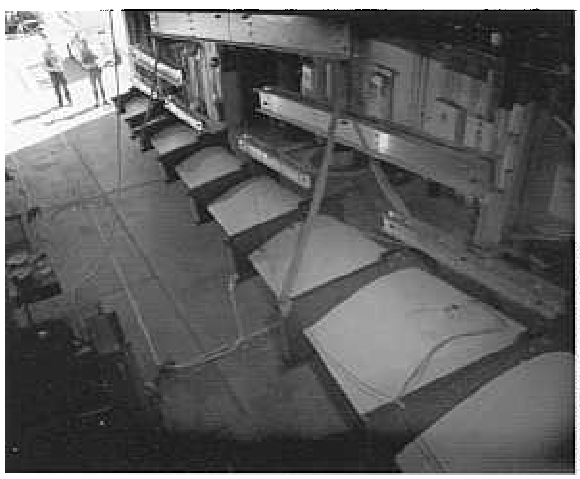
Structural testing offers many benefits to wind turbine companies. Wind turbine companies use Center facilities to verify and improve new blade designs, analyze blade structural properties, and help improve manufacturing processes. Blade testing can provide important information that helps accelerate the design process. Nondestructive testing techniques provide cost-effective methods for determining how blades age and predicting service life and maintenance requirements.

Comprehensive structural testing can assure turbine customers that a blade is adequately designed. Prototype field testing seldom offers this assurance, because prototype machines seldom encounter the most extreme conditions during testing. In contrast, structural testing puts a blade through its entire design life cycle.

When purchasing wind turbines, customers seek more than assurances, however. Many require that the wind turbines they purchase be certified. Blade testing is an important part of the international certification process. Although no U.S. organization currently certifies wind turbine systems, U.S. turbine manufacturers use test results from the Center in seeking certification for their turbines in Europe. They also use the test results to affirm the quality of U.S. turbine technology in foreign markets.

## STRUCTURAL-TESTING FACILITIES

The National Renewable Energy Laboratory (NREL) has three wind turbine blade test facilities, including a new high bay in the Industrial User Facility. The high bay is large enough to test any blade expected during the next five years. Two testing areas are equipped with stands rated at 1 million foot-pounds capacity; the other has a 4 million foot-pound stand. Each area has an overhead crane for applying loads to the blade during static-strength testing.



Warren Gretz, NREL PIX 00213

*During ultimate static-strength testing at the National Wind Technology Center, loads are distributed across multiple points on the blade (shown above) or concentrated in a single location. The maximum static load is 35 tons.*

The test areas have closed-loop servo-hydraulic systems for fatigue testing. With the system, operators can apply loads, vary the amplitude of loads on the blade, deflect blades, and change the frequency and location of loading. The system capabilities are adequate to perform certification testing for blade design standards.

In 1995, NREL's National Wind Technology Center developed a sophisticated data acquisition system, known as the Blade Structural Testing Real-time Acquisition Interface Network, or BSTRAIN, to monitor structural testing. The system is based on LabView software developed by National Instruments. The same company manufactured signal-conditioning hardware that routes data from blade tests into BSTRAIN for monitoring and analysis.

The new system provides great flexibility in test monitoring and data analysis. It can automatically collect blade test data as well as permit selective manual operation. BSTRAIN allows 24-hour continuous video surveillance of tests to ensure that critical events are monitored during unattended operation. It is capable of detailed analysis of structural tests, early detection of blade problems, automatic control of signal drift, and recording blade stiffness changes throughout the test.

## Recommended Tests

The National Wind Technology Center recommends both ultimate static-strength and fatigue testing for wind turbine blades. Both tests are necessary to verify a new blade design. In some cases, researchers may recommend nondestructive evaluations to obtain more detailed information about failure modes and assess quality assurance procedures.

### Ultimate Static-Strength Testing

Ultimate static-strength testing helps turbine designers predict a blade's ability to withstand extreme loads such as those caused by hurricane-force winds or unusual transient conditions. Designers use static-strength tests to compare a blade's actual strength with design specifications and determine whether their buckling analysis was correct.

### Fatigue Testing

By simulating continuous operating loads, fatigue testing helps designers understand blade materials and the structural details of the design. Structural details such as joints, ply drops, and geometric transitions are more difficult to model during early design work and are often the weak link in a blade's structure.

### Vibration Testing

Vibration testing identifies a structure's natural vibration frequencies. The information sheet entitled *Vibration Testing* describes the Center's vibration-testing capabilities.

### Nondestructive Testing

Unlike the tests described above, acoustic emissions, ultrasonic, and photoelastic strain tests do not damage blades. Acoustics testing identifies possible failure locations during static-strength or fatigue testing. Researchers attach microphones to a turbine blade under test. As loading increases on the blade, glass fibers break in areas experiencing high strain, creating pinging sounds.

Researchers use ultrasonic testing to examine high-strain areas identified during acoustics testing or from previous static and fatigue tests. A signal sent into the blade goes through (undamaged) smooth laminate, but bounces off any air gaps, pinpointing flaws beneath the blade's surface.

During photoelastic strain testing, researchers identify strain patterns on turbine blades by coating them with a strain-sensitive material. When viewed under polarized light, colorful strain patterns are clearly visible. The strain patterns can be used to infer stress patterns and blade loads.

Nondestructive tests are conducted in collaboration with researchers from Sandia National Laboratories.

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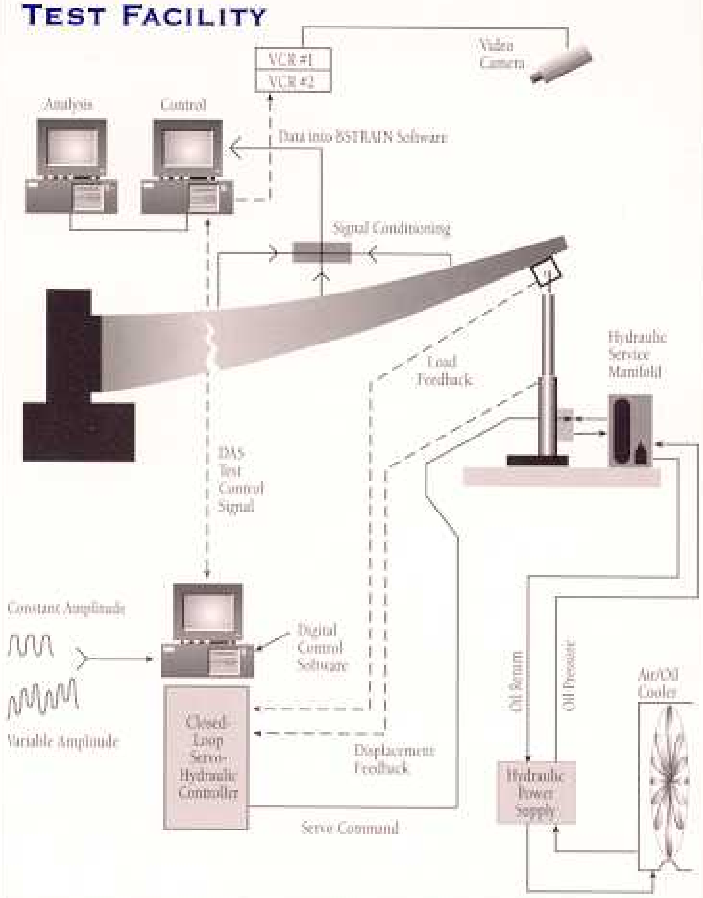
e-mail: walter_musial@nrel.gov

## Structural Test Facility




## Structural-Testing Equipment

| | |
|---|---|
| Number of Test Bays | 4 |
| Maximum Blade Length | 100 ft |
| Maximum Test Stand Capacity | one @ 4 million ft-lb<br>two @ 1 million ft-lb |
| Fatigue Test System | Closed-loop servo-hydraulic |
| Maximum Oil Flow | 75 gpm |
| Maximum Fatigue Load | 28,000 lbs |
| Maximum Fatigue Stroke | 50 in. |
| Maximum Static Test Load | 70,000 lbs |
| Maximum Static Displacement | 20 ft |
| Data Acquisition System | National Instruments |
| Software | LabView, BSTRAIN, NREL custom |
| Maximum Data Channels | 48 |

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# Vibration Testing

The National Wind Technology Center offers modal and vibration testing as part of its comprehensive structural-testing program. A fully equipped mobile test van allows engineers to conduct vibration testing on wind turbines anywhere in the United States.

The wind industry can also take advantage of advanced modal-testing equipment, software, and trained engineering specialists at the Center, located near Golden, Colorado. Modal testing allows engineers to identify the natural vibration frequencies of turbine components such as blades and towers. It is performed by shaking a wind turbine that is not operating, then measuring the structural vibrations with accelerometers attached to the structure at key positions. Vibration testing uses the same instruments to measure operating deflections of the turbine that occur during normal or abnormal operation.

## Uses of Modal and Vibration Testing

The wind industry can use modal and vibration testing to validate and update computer models, to troubleshoot operational problems, to understand operational loads, to detect interactions between turbine components that cause unwanted vibrations, and to evaluate the impacts of design changes.

### Validation of Analytical Models

Modal testing has become an integral part of computer-aided product design and development. It provides important feedback to designers on the modal characteristics of new components and systems. The modal test data allows designers to validate and refine the analytical models used in turbine design.

### Troubleshooting Operational Problems

Modal testing can identify potential or existing problems with operating wind turbines. An operating turbine can experience a resonant (and potentially damaging) vibration if the turbine operates near one of its natural vibration frequencies. To identify problems, a modal test is performed in the field. Results can be obtained immediately by graphing the data to produce a plot known as a Campbell diagram, which compares the machine's natural vibration frequencies with the operating speeds of the turbine.

The coincidence of a natural frequency with a per revolution forcing frequency of the rotor identifies a potential resonance condition.

Warren Gretz, NREL PIX 00213

*Researchers perform vibration tests on a newly designed wind turbine blade in the high bay at the National Wind Technology Center.*

### Understanding Operational Loads

Engineers use vibration testing to help them understand operational loads on a wind turbine. Most turbine manufacturers gather information on operational loads, such as the blade flap bending moment and the tower bending moment, by attaching strain gauges to the machine and measuring deflections as a function of time. Often, this data is used to produce a power spectrum, a graph of the amplitude of a response versus frequency. This power spectrum is the sum of the machine's natural vibration responses and responses due to machine operation, known as forced responses. Forced responses result from nonrandom problems such as blade pitch and mass imbalances. Natural responses result from random excitation caused by turbulence in the wind.

Modal tests help engineers sort out the forced and natural responses and understand the loads in terms of their origin. Modal tests also provide information on how natural and forced responses interact. This information helps wind turbine designers avoid resonances, which occur when forced responses coincide with natural responses.

## Analysis of Complex Vibrational Patterns

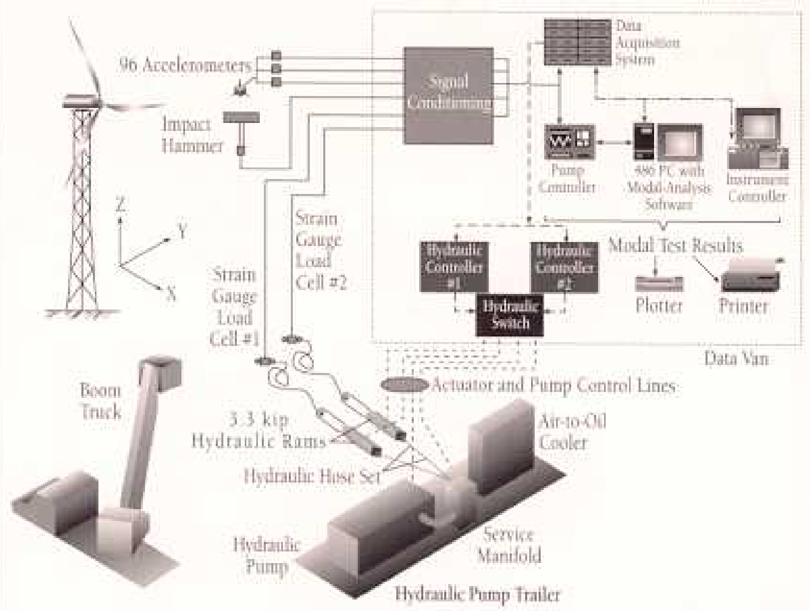
When modal tests are done in the field, engineers often conduct vibration tests at the same time. Because the machines are already instrumented with accelerometers from the modal testing, it is relatively easy to gather data on the deflection of key structures during operation. This experimental information is then used to animate a model of the structure at a given frequency on the computer. Analytical models such as ADAMS (a powerful turbine design code) or a finite element analysis code can also be used to create the animation.

The animated structures allow design engineers to look at turbine operation from the perspective of an outside observer. It is particularly useful to create an animated wind turbine at frequencies in which large peaks in the power spectrum occur. Often, coupled vibration responses such as a nacelle pitch and tower bending show up. Once a complex vibration pattern has been identified, design engineers can use their analytic software to develop ideas for design changes to remedy the problem. Specialists in vibration testing at the National Wind Technology Center use modal and vibration test data to analyze the turbine's response to proposed design solutions.

## Control System Modeling and Design

Modern control systems for flexible, dynamic mechanical structures such as wind turbines are designed with the structure's modal response in mind. Typically, a turbine designer will model a turbine design's natural vibration responses and system dynamics before designing a smart control system. This information allows the control system designer to predict the turbine's controlled behavior in many different environments.

## Modal Test Setup




## Modal Test Equipment

| Component | Rating/Size |
|---|---|
| Dual Hydraulic Actuators | 3.3 kip |
| Air-Cooled Hydraulic Pump | 23 gal/min; 3000 psi |
| 2 Pump Controllers | |
| Data Acquisition System, UNIX Instrument Controller | 96 channels |
| Low-Frequency, High-Resolution Accelerometers | 96 (21 triax or 31 biax) |
| Low-Noise Conditioning System | |
| Structural Testing and Modal Analysis Software | CADA-X |
| Strain Gauges | |
| GM/Itasca Van, Hydraulic Pump Trailer | |

## Vibration Testing Capabilities

Because the wind industry often needs vibration tests done in the field, the National Renewable Energy Laboratory developed a mobile testing laboratory. A specially designed van houses a computer system and test equipment. A trailer carries a hydraulic pump and associated equipment. Test equipment includes a dual hydraulic shaker system controlled by a computerized data acquisition system. The shaker system consists of hydraulic actuators powered by an air-cooled hydraulic pump.

Ninety-six low-frequency, high-resolution accelerometers placed on the wind turbine measure the machine's response to the shaker. Signals from the accelerometers pass through a low-noise conditioning system into the data acquisition system. The low-noise signal-conditioning system is necessary to measure the low-frequency natural vibration characteristics of a wind turbine. The data acquisition system is controlled by a high-speed, UNIX-based instrument controller. Special modal analysis software automatically determines natural vibration modes and turbine operating loads.

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